1.5 Gbps PN-ZP-DMT Transmission System for 1-mm Core Diameter SI-POF with RC-LED

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(1) IETR, UMR 6164, INSA-Rennes, Université Européenne de Bretagne, 35708 Rennes, France
{linning.peng, sylvain.haese, maryline.helard, ming.liu}@insa-rennes.fr

Abstract *A novel PN-ZP-DMT transmission scheme without requiring dedicated pilots for channel estimation is proposed. Hardware experiments on 50 m SI-POF with RC-LED show that the proposed scheme achieves a transmission rate of 1.5 Gbps with low cost off the shelf components.*

Introduction

Recently, 1 mm large core diameter plastic optical fiber (POF) attracts a lot of attention for in-door optical connections. POF owns the advantages of easy connection and bend insensitivity. However, the 3 dB bandwidth of POF is limited due to the significant modal dispersion in large core diameter POFs[1]. Multi-carrier modulation schemes, such as discrete multi-tone (DMT), were employed in POF transmissions in order to extend the transmission bandwidth beyond POF's 3 dB bandwidth[2]. With the help of bit-loading techniques, DMT scheme can exploit a transmission bandwidth much larger than the 3 dB bandwidth[2]. Traditionally, pilots are needed in DMT for channel estimation. Recently, a pseudo-noise (PN) sequence assisted orthogonal frequency divided multiplexing (OFDM) system was proposed and used for digital video broadcasting systems[3]. Instead of classic cyclic prefix (CP) in the OFDM system, a PN sequence is used instead of the guard interval and reused as the training sequence for channel estimation to achieve higher spectral efficiencies[3]. Meanwhile, in order to improve system power efficiency, zero-padding (ZP) OFDM systems were recently proposed for optical OFDM system[4]. In[4], the scattered time-frequency pilots for channel estimation in optical OFDM system was investigated, which can improve the pilot occupation ratio from 9.16 % to 2.48 %, compared to conventional CP-OFDM system.

In order to further improve the system efficiency, we propose a PN-ZP-DMT scheme for POF transmission system. Compared to the existing CP-OFDM and ZP-OFDM systems, the proposed system does not need any pilots dedicated to channel estimation, which further improves the system efficiency. Furthermore, it is shown through a 50 m Ø1mm step-index (SI) POF system that the proposed scheme achieves a 1.5 Gbps transmission rate even with very low cost components.

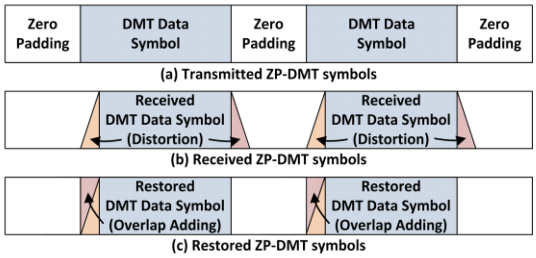


Fig. 1: Illustration of ZP-DMT system

Zero-padding DMT Transmission System

Fig.1 illustrates the signal waveform of the ZP-DMT system. Compared to the traditional CP assisted DMT system, CP symbols are replaced by a series of zeros in ZP-DMT transmission system. The received DMT symbols are distorted due to the channel memory, as shown in Fig. 1(b). Overlap and add technique is employed to restore the cyclicity in received ZP-DMT symbols[4]. Therefore, DMT symbol can be easily recovered in the frequency domain as it does in the traditional CP assisted DMT systems, as shown in Fig. 1(c). The transmitted signal power is saved in the ZP symbols.

Pseudo-noise DMT Transmission System

An overall system diagram of the PN-DMT scheme is demonstrated in Fig. 2. Being different from the ZP-DMT scheme, the PN-DMT scheme employs PN sequences instead of zeros between two consecutive DMT data symbols. At the receiver, PN sequences and DMT symbols overlapped due to the channel memory effect, as shown in Fig. 2(b). As the PN

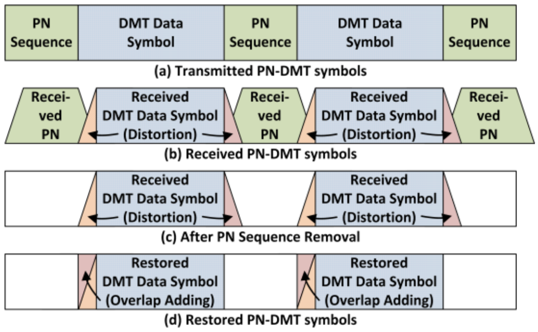


Fig. 2: Illustration of PN-DMT system

sequences are known by the receiver, it is easy to remove them from the received PN-DMT symbols. After removing PN, received PN-DMT symbols are turned into equivalent ZP-DMT symbols, as shown in Fig. 2(c). DMT symbols can be restored with the same process as it in ZP-DMT.

Furthermore, it is worth noting that the channel impulse response (CIR) can be estimated using PN sequence[5]. In order to reduce the estimation error in PN-DMT system, a CP is added to PN sequence to reduce the interference in the PN sequence based channel estimation[5].

Proposed PN-ZP-DMT Transmission System

In PN-DMT transmission system, the longer the PN sequence, the lower the residual error after equalization[5]. However, excessively long PN sequences decrease the overall system efficiency. Furthermore, it is well known that the optical fiber channel is relatively stable. Therefore PN sequence is deployed just before the first DMT symbol, and then zeros are inserted between the consequent DMT symbols, which yield a hybrid PN-ZP-DMT transmission scheme. The CIR is estimated using the first PN sequence and is used to equalize following DMT symbols. In addition, the length of padded zeros can be adaptively adjusted according to the estimated CIR obtained using PN sequences. The structure of proposed PN-ZP-DMT scheme is shown in Fig. 3. By optimizing the length of the PN as well as the length of the ZP, the proposed hybrid PN-ZP-DMT scheme can maximize the system performance and efficiency in POF.

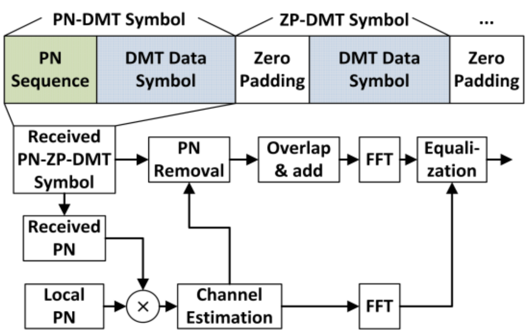


Fig. 3: Receiver structure of proposed PN-ZP-DMT scheme and PN-based channel estimation

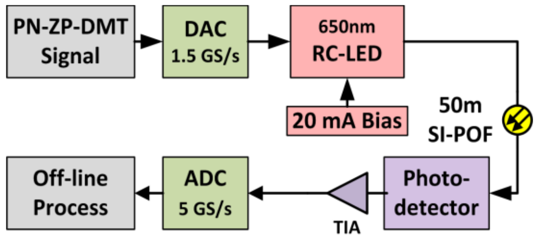


Fig. 4: Experimental system setup

Experimental Setups and Results

The hardware experimental system is setup according to the diagram in Fig. 4. A low-cost 650 nm wavelength resonant cavity light emitting diodes (RC-LED) was directly modulated by the output of arbitrary waveform generator (AWG). AWG works at 1.5 G Samples/s. A biasing current is added to bias the RC-LED. The optical power fed into the SI-POF is -0.2 dBm. After the transmission over 50 m SI-POF (Ø1mm Eska™ Mega), the received optical power is -9.4 dBm. A Si-PIN photodetector converts the optical signal to electrical signal, which is consequently amplified by a trans-impedance amplifier (TIA) and finally captured by a digital oscilloscope.

2000 DMT symbols with 512 subcarriers and a bandwidth of 375 MHz are generated in Matlab™. According to the frequency response of this SI-POF system, the first three subcarriers and subcarriers form 414 to 512 are set to null. The used bandwidth is around 300 MHz. As the AWG works at 1.5 G Samples/s, 4x oversampling is performed. The first transmitted DMT symbol is a PN-DMT symbol. Instead of the CP in traditional DMT systems, a PN sequence with a length of 288 samples (255-length PN sequence + 33 CP samples of the PN) is added before the first DMT symbol. After the first PN-DMT symbol, the subsequent DMT symbols are ZP-DMT symbols. To prevent the inter-symbol interference, the length of padded zeros should be longer than the maximum multi-path delay. It is set to 24 ns (32 samples) according to 50 m SI-POF channel measurement. In order to eliminate the channel estimation error caused by sampling frequency offset between DAC and ADC, a PN-DMT is repeatedly transmitted every 20 DMT symbols. The overall system overhead for the PN

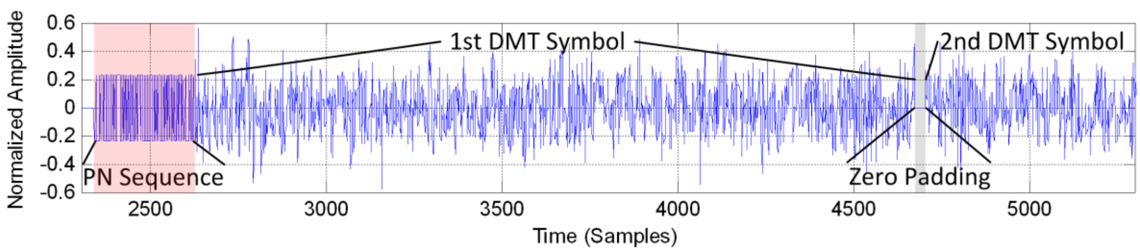
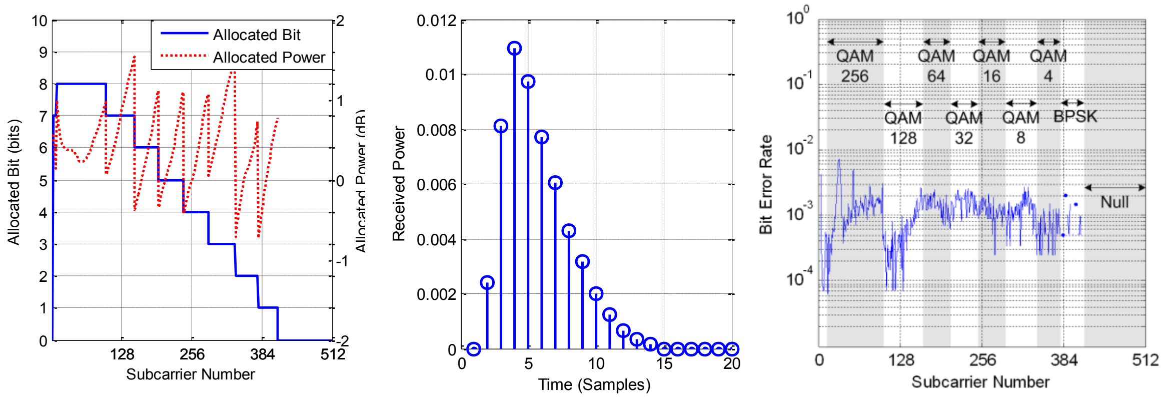


Fig. 5: Demonstration of generated PN-ZP-DMT waveform



(a) Power & bits allocation in DMT **(b)** Estimated CIR from PN **(c)** Uncoded BER

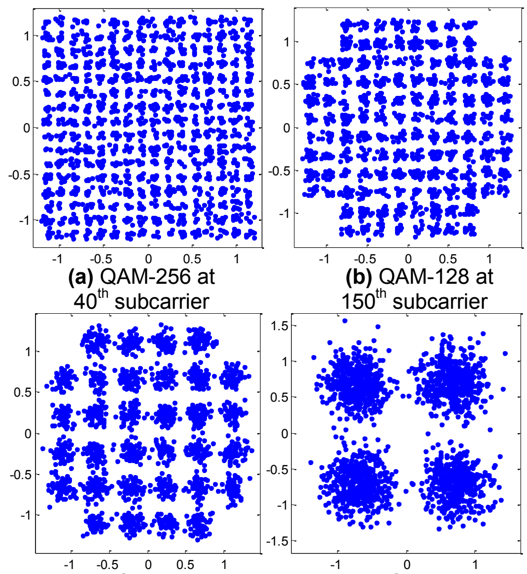
Fig. 6: Experimental results

sequence channel estimation is only 0.6 %, which is significantly less than the pilots based systems[4]. A demonstration of the generated PN-ZP-DMT symbols is presented in Fig. 5.

Different subcarriers are allocated with different modulation orders and power, which is shown in Fig. 6(a). The objective bit error rates (BER) is 1×10^{-3} and 0 dB signal-to-noise ratio (SNR) margins in set for the bit-loading. Finally, 2069 bits are allocated in 410 subcarriers, with modulations ranging from QAM-256 to BPSK. The approximate net transmission rate R is calculated as:

$$2069 \times (1.5 \times 10^9 \div 2080) \times 99.4\% \approx 1.48\ Gbps$$

After a transmission over 50 m SI-POF system, CIR is estimated from the first PN sequence. The obtained CIR is shown in Fig. 6(b). A total uncoded BER of 1.2×10^{-3} is achieved, which is very close to the objective BER with 0 dB SNR margins. The BER in different subcarriers is given in Fig. 6(c). More interestingly, it can be seen that DMT symbols with QAM-256 modulation can be accurately demodulated, which demonstrates the advantage of the proposed scheme. In addition, the constellation diagrams of the demodulated signals with QAM-128, QAM-32 and QAM-4 are shown in Fig. 7.



(a) QAM-256 at 40th subcarrier **(b)** QAM-128 at 150th subcarrier

(c) QAM-32 at 240th subcarrier **(d)** QAM-4 at 340th subcarrier

Fig. 7: Constellation diagrams of the demodulated PN-ZP-DMT signals

Conclusions

We proposed a novel PN-ZP-DMT scheme for OFDM based optical communication system. PN sequence based channel estimation for DMT system is demonstrated. In combination with adaptive ZP length, the hybrid PN-ZP-DMT scheme can maximize the system transmission efficiency. Compared to the traditional optical OFDM system with dedicated pilots for channel estimation, the novel PN-ZP-DMT scheme can further improve the system transmission efficiency. Employing low cost RC-LED, 1.5 Gbps transmission has been achieved over 50 m Ø1mm SI-POF with a spectral efficiency of 4.9 bits/s/Hz. Owning to the low residual error after PN sequence channel estimation, high order modulation such as QAM-256 can be correctly demodulated. In addition, the proposed PN-ZP-DMT scheme can be easily employed in other optical fiber transmission systems and is a promising technique to improve system efficiency in optical OFDM system.

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